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# LEAN, PREMIXED, PREVAPORIZED COMBUSTION FOR AIRCRAFT GAS TURBINE ENGINES

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## Abstract

The application of lean, premixed, prevaporized combustion to aircraft gas turbine engine systems can result in benefits in terms of superior combustion performance, improved combustor and turbine durability, and environmentally acceptable pollutant emissions. Lean, premixed prevaporized combustion is particularly attractive for reducing the oxides of nitrogen emissions during high altitude cruise. The NASA Stratospheric Cruise Emission Reduction Program will evolve and demonstrate lean, premixed, prevaporized combustion technology for aircraft engines. This multiphased program is described. In addition, the various elements of the Fundamental Studies Phase of the program are reviewed, and results to date of many of these studies are summarized.

## Introduction

This paper reviews the ongoing NASA sponsored Stratospheric Cruise Emission Reduction (SCERP) Program, and presents an overview of the Fundamental Studies phase of the program.

Concern over air pollution has drawn the attention of combustion engineers to the quantities of exhaust emissions produced by aircraft gas turbine engines. Two general areas of concern have been expressed: Urban pollution in the vicinity of airports and pollution of the stratosphere. The principle urban pollutants are unburned hydrocarbons (HC) and carbon monoxide (CO) emitted by engines during idle and taxi operations of aircraft; and oxides of nitrogen ($NO_x$) and smoke emitted during takeoff and landing operations of aircraft. The pollutants of concern during high altitude cruise of aircraft are primarily oxides of nitrogen emissions from engines. For a number of years NASA Lewis Research Center has been engaged in research efforts to reduce the levels of these pollutants through in-house research, university grants, and industry contracts.

Two government sponsored studies regarding the potential impact of aircraft exhaust emissions in the upper atmosphere (stratosphere) have concluded that the $NO_x$ emitted by future fleets of high altitude cruise aircraft could adversely influence the stratospheric ozone concentration and the earth's albedo.[1,2] More recent studies[3-5] suggest that effects are less than previously estimated. However, these reports indicate that there still exist major uncertainties and gaps in our knowledge that preclude accurately forecasting the magnitude of these effects. For example, Poppoff, et al. state in their concluding remarks that "it must be emphasized that this evaluation is subject to change as our knowledge of the stratosphere expands."[5] And from the report of the first meeting of the International Civil Aviation Organization Committee on Aircraft Engine Emissions: "the present understanding of climate was (sic) insufficient to permit reasonably accurate prediction of the net climatic change which might be caused by stratospheric flight. . . It was (sic) possible that future changes in the estimates could lead to substantial modifications in the conclusions."[6] Consequently, the reduction of $NO_x$ emission levels has been and still remains a desirable principal design goal for future aircraft gas turbine engines.

To achieve substantial reductions in $NO_x$ emission levels from engines operating at aircraft cruise and takeoff conditions, major advances in combustion system technology are required. A previous NASA sponsored program, the Experimental Clean Combustor Program, demonstrated advanced combustors in engines which produced lower $NO_x$ emission levels than exist for conventional combustion technology.[7,8] But to achieve the factor of 10 or greater $NO_x$ emissions reduction at the cruise operating condition, as recommended in Ref. 2, a more advanced technology is needed. A technique for achieving low $NO_x$ emission levels has been experimentally demonstrated in a "flame-tube rig" in which fuel and air are premixed and prevaporized prior to combustion.[9] A composite representation of results obtained from these "flame tube rig" tests is shown in Fig. 1. At the test conditions indicated, extremely low levels of $NO_x$ emissions (emission index < 1 g/kg) were obtained at very lean equivalence ratios, $\phi$. These low $NO_x$ E.I. values were obtained at reasonable residence times (about 2 msec) and at combustion efficiencies in excess of 99.7% This type of data shows the potential of utilizing lean, premixed, prevaporized (LPP) combustion in aircraft gas turbine engine combustor systems.

The successful application of LPP combustion to practical aircraft engine systems will require consideration of many factors and requirements. For example, the fuel-air mixture residence times needed for fuel vaporization prior to entering the burning zone of the combustor may contribute to the occurrence of autoignition under operation at the high inlet temperatures associated with takeoff. Also, the airflow rate into the front of the burner needed to establish lean combustion during high power operation may result in flame blowout tendencies at lower power conditions. Acceptable performance in terms of fuel consumption (combustion efficiency), as well as durability, maintainability, and safety considerations must be taken into account for future application of LPP combustion techniques in engine combustors.

With these above considerations in mind, NASA Lewis Research Center established the Stratospheric Cruise Emission Reduction (SCERP) Program. This program will now be briefly described.

## SCERP Program Description

### Program Objective

The objective of the SCERP Program is to evolve lean, premixed, prevaporized combustion technology into a practical aircraft gas turbine engine combustion system that exhibits superior performance, high durability, and environmentally acceptable pollutant emissions over the entire flight envelope. Special emphasis is being placed on achieving very low oxides of nitrogen emissions levels at stratospheric cruise conditions. The application of this combustion technology would be aimed at future advanced fuel efficient aircraft gas turbine engines that have high pressure ratios (30:1 or higher) and high temperature rise combustor requirements.

## Program Goals

There are a number of goals for the overall SCERP program, including emissions goals, performance goals and operation goals. The emissions goals are listed in Table 1. Near-airport goals are given in terms of the Environmental Protection Agency (EPA) parameter, or EPAP, which is defined over a standard landing-takeoff cycle. The values of these pollutant goals are chosen to be 25% below the current EPA Emission Standards for newly certified engines for 1981 and beyond, as specified in Ref. 10. The 25% difference between the goals and the current EPA Standards was established to provide margin for later engine development and production variations. These program goals are compared in Table 1 with engine results from the above mentioned NASA Experimental Clean Combustor Program (ECCP). Both carbon monoxide and oxides of nitrogen results from the ECCP tests are considerably above the SCERP program goals. Note that the value of $NO_x$ for the JT9D-7 engine tests would likely be higher still if the pressure ratio of that engine were to increase from 23:1 to the 30:1 value which is more typical of future gas turbine engines.

A more stringent $NO_x$ goal is the one shown in Table 1 for aircraft cruise operation (typically, at 10.7 km, 0.80 flight Mach No.). Up to almost an order of magnitude reduction in $NO_x$ from current engine emission levels is required to meet the goal.

The program performance goals are shown in Table 2. These goals are guidelines for the design and refinement of combustor concepts during the program. The final evolved combustor system from this program will be evaluated using these goals.

There are many operational considerations or goals for this program and they are listed in Table 3. These goals will be especially addressed in the latter part of the SCERP program and the final evolved combustor system will be evaluated against these operational considerations.

## Program Benefits

The successful development of lean, premixed, prevaporized combustion technology into a practical aircraft engine combustion system could result in the following benefits to future advanced aircraft engines:

(a) A reduction of aircraft cruise $NO_x$ emissions to 10% of current levels.

(b) Near airport emissions of CO, HC, $NO_x$, and smoke reduced to meet 1981 EPA Standards.

(c) A significant increase in combustor liner life or liner durability, due to a reduced heat load from the lower burning zone flame temperature, and from the elimination of liner hot spots through the very uniform temperature of the burning zone.

(d) A significant improvement in turbine life or turbine durability from the elimination of hot streaks and from low turbine nozzle profile factors due to the uniform temperature of the burning zone in the combustor.

(e) Superior combustor performance through the use of combustor variable geometry to control airflow to increase combustion stability at altitude relight and idle operating conditions.

## Program Approach

The SCERP program was initiated to verify the potential of applying lean, premixed, prevaporized (LPP) combustion to advanced aircraft engine systems. The program is divided into four parts as shown in Table 4. Prior to examining LPP combustor concepts themselves a Fundamental Studies Phase was begun in 1976 to examine various aspects of LPP combustion which were identified as requiring more understanding. Many of these Phase I projects are now completed with the remainder to continue over the next few years, as signified in the Table by the tapering activity bar. The remaining efforts of this program are planned to be conducted in three phases over the next 4 years through contracts with industry.

### Phase II - Combustor Concept Screening

This phase of the program will concentrate on converting the fundamental knowledge obtained previously into an integrated combustor system that is capable of operating in an actual aircraft engine environment. This phase will consist of a series of designs, tests, design modifications, and retests to determine promising combustor configurations. Evaluation of the combustors will be based primarily on performance and pollutant emissions, especially cruise $NO_x$ emissions.

### Phase III - Combustor Refinement

This phase will concentrate on converting the one or two best Phase II concepts into integrated combustor and associated control systems for an existing aircraft engine. A series of tests, design modifications, and retests will be conducted to evolve practical combustion systems and associated controls for engine adaptation while maintaining good performance and pollutant emissions characteristics. System durability and reliability will be emphasized.

### Phase IV - Engine Verification

Based on the results of Phase III, the optimal combustor and associated control systems will be designed and fabricated for testing as part of a complete engine. The engine will undergo static tests to document the performance, pollutant emissions, and operational characteristics of the combustor system. The engine selected for this phase of the program must be available for use as a test bed for the evolved combustor in the 1983 time frame. It does not necessarily represent an advanced technology engine in which an LPP combustor might later be developed specifically for use.

At this time in the program, work on Phase II has not yet begun. But much information, forming a data base of fundamental knowledge on LPP combustion, has been obtained through the Phase I activities. The work in Phase I will now be discussed.

## Phase I - Fundamental Studies

Before combustor concepts could be designed for practical engine operation, various aspects of LPP combustion were identified as requiring more understanding. Research efforts in these areas comprise the Phase I Fundamental Studies portion of the program. Early in Phase I a workshop was held as a means of bringing together combustion experts from government, universities, and industry to examine the state of the lean, premixing, prevaporizing combustion concept, and to review the NASA SCERP Program and invite comments on its technical merits.[11] Seventeen participants met for 2 days. The findings of this workshop were considered in the structuring of the scope and direction of the Phase I effort. Since the field of LPP combustion is so broad and complex the research activities were compartmentalized into four separate technical areas. Of course some degree of overlap occurs in the definition of the areas, but this method serves to illustrate the major thrusts of effort. The four elements of Phase I are: Lean Combustion, Fuel-Air Preparation, Autoignition and Flashback, and Engine Interfaces.

In the area of Lean Combustion, the main objective is to examine the factors influencing the performance and emission characteristics of LPP combustors. These factors include combustor operating conditions (pressure, temperature, and burning zone equivalence ratio), residence time, reference velocity, combustor geometry, and fuel-air mixing characteristics.

A basic requirement of LPP combustion is to supply the combustion zone with a homogeneous mixture of air and fuel vapor over a wide range of engine operating conditions. Under the Fuel-Air Preparation element, information is being sought on important parameters of fuel injectors, such as spray angle, drop-size distributions, degree of vaporization, and uniformity of fuel-air mixing. Moreover, the impact of these parameters on $NO_x$ formation is being sought.

An intrinsic feature of LPP combustion is a tendency towards autoignition and flashback. Thus, before the system can be applied with confidence to a modern high pressure ratio engine, the flame stability and spontaneous ignition characteristics of premixed fuel-air systems must be properly understood. This understanding is being acquired in the Autoignition and Flashback element.

The Engine Interfaces element is concerned with the combustor environment inside an engine and the constraints imposed on the combustion system through interface with the engine.

The research efforts under each element of the Fundamental Studies Phase are shown in Table 5. As indicated by the parentheses in the table, these research projects include contracts with various research groups and engine manufactures, grants with universities, and in-house (IH) research at the NASA Lewis Research Center. Most of these projects are either already completed or will be completed by the end of 1979. A review of most of these projects and other work sponsored by Lewis Research Center which applies to LPP combustion was conducted in January 1979.[12] A brief overview or highlighting of each of these research efforts will now be given. More detailed information may be obtained through Ref. 12 or through other indicated references.

### Lean Combustion Element

Effect of Cycle Pressure on Lean Combustion Emissions. Tests were conducted in a high pressure flame tube using propane fuel.[13-15] A summary of the results is shown in Fig. 2. Emissions of oxides of nitrogen are shown as a function of the adiabatic flame temperature. Data over the ranges of inlet pressure and temperature shown are all represented by the single bar in the figure. Three noteworthy accomplishments are results of this work. First, early flame tube experiments had not been conducted at pressures much above 10 atmospheres. Successful operation of a flame tube at pressures to 30 atmospheres and at inlet-air temperatures comparable to those of modern engines was significant. Second, previous data has shown an inconsistent trend in $NO_x$ as the pressure was increased. In this experiment there was no effect of pressure found on $NO_x$ emissions over a range of pressures from 10 to 30 atmospheres from a lean premixed prevaporized combustion system when correlated against adiabatic flame temperature. Third, this experiment verified, in a more realistic environment, the emission levels projected from the lower pressure tests of Fig. 1. A conventional combustor at takeoff conditions has an emission index of 30 to 40. To achieve the same required temperature rise, data from this figure indicate that a completely premixed combustor would have a $NO_x$ emission index of around 1 or 2.

Effects of Flameholder Geometry on Emissions and Performance of Lean Premixed Combustors. Emission levels and performance of 12 flameholder designs were investigated in a lean, premixed propane-air system at inlet conditions of 800 K and 10 atmospheres.[16] Shown in Fig. 3 is the flame zone structure for six of the flameholder concepts, including wire grid, perforated plate, cone, and "C" gutter. The open duct burning photographs shown here were taken only for visualization purposes since actual testing was done at high pressure; wide differences in flame structure are evident from the photographs. Test results found flameholder pressure drop to be a principal determinant of emissions performance. Designs producing larger pressure drops resulting in higher turbulence also produced less emissions. Also, the lean stability limit equivalence ratio was found to be approximately 0.35 for all designs.

Lean Stability Augmentation Study. An analytical conceptual design study and an experimental test program were conducted to investigate techniques for improving the lean combustion limits of premixing, prevaporizing combustors applicable to gas turbine engine main burners.[17-18] A total of 16 test configurations of flameholders was examined in a flametube test rig at a pressure of 10 atmospheres and at a range of elevated entrance temperatures. Lean blowout limits, pollutant emission characteristics, and combustor performance were documented. The most promising configuration identified in this program involved the injection of pilot fuel into the base or recirculation region of a bluff body flameholder. With a pilot fuel flow of 4% of the total fuel flow, combustor blowout did not occur as fuel flow was decreased to levels corresponding to an overall equivalence ratio of 0.25. This is illustrated in Fig. 4 where the blowout limit of the unpiloted flameholder is shown. No blowout was observed over the range of inlet temperatures from 600 to 800 K with the piloted flameholder.

Secondary Air Dilution Study. A research project is underway to measure the effects of dilution air addition on the emissions and stability of an LPP gas turbine combustor. A flame tube test rig is being designed and fabricated which will allow flow visualization, tracer testing, and combustion testing to be carried out while varying the amount of air added in each of two dilution stages. The test rig simulates the internal geometry of an LPP combustor. This project will be completed near the end of 1979.

Effects of Flameholder Blockage on Emissions and Performance. Studies of the effects of flameholder blockage were conducted in a flame tube experiment, at pressures of 3 to 5 atmospheres and inlet temperatures from 600 to 800 K using Jet A liquid fuel. Test results support the theory that flameholder blockage affects the size and shape of the recirculation zone behind the flameholder and thus affects the emissions levels. Increasing flameholder blockage increases $NO_x$ emissions.

Effects of Degree of Fuel Vaporization and Fuel-Air Ratio Nonuniformity Upon Emissions. Two parallel studies were conducted in an LPP combustor flametube test rig. The objective of the first study was to assess the impact of the degree of fuel vaporization on emissions from a flame tube combustor burning a premixed, "partially vaporized" fuel-air mixture.[19] The tests were conducted at an inlet pressure of 3 atmospheres and inlet temperatures of 600 to 700 K using Jet A liquid fuel. The results are summarized in Fig. 5 which displays an effect of vaporization on $NO_x$ which differs with equivalence ratio. For an equivalence ratio of 0.6, decreasing the fuel vaporization leads to a nearly linear increase in $NO_x$. However, for an equivalence ratio of 0.72, changes in vaporization had very little impact on $NO_x$ emissions.

The objective of the second study was to determine the effect of fuel-air ratio nonuniformity on $NO_x$ emissions using the previously mentioned test hardware. Test conditions were similar. Test results are summarized in Fig. 6 and indicate that for a given overall equivalence ratio, as the degree of nonuniformity increases for the fuel-air ratio distribution, the overall mean value of $NO_x$ will significantly increase until local values of equivalence ratio exceed stoichiometric.

Lean, Premixed, Prevaporized Combustor Conceptual Design Study. Before undertaking the design and testing of combustor hardware in the Phase II portion of the SCERP Program, it was felt that a design study should be conducted, using all the information to date from the Phase I Fundamental Studies efforts, to examine potential combustor concepts in a systematic manner. Two contractors, the Aircraft Engine Group of General Electric Company and Pratt and Whitney Aircraft Group of United Technologies Corporation are performing studies to identify and evaluate promising LPP combustor concepts with regards to their potential for meeting performance, emissions, and operational requirements of advanced aircraft engines. Each contractor is examining four combustor concepts; these concepts are shown in Figs. 7 and 8. Variable geometry of combustor hardware, multiple fuel staging and multiple burning zones are features of these combustor concepts. These features enable the concepts to be optimized at several different operating conditions. Advanced combustor liner cooling technology is also employed in these concepts to maximize the amount of air available for the lean burning of fuel and for tailoring the turbine nozzle inlet temperature profile.

Fuel-Air Preparation Element

Experimental Study of the Operating Characteristics of Premixing-Prevaporizing Fuel-Air Mixing Passages. Successful application of LPP combustion requires an understanding of the operational characteristics of a fuel-air preparation section. The performance of an LPP combustor depends upon the mixing and distribution of fuel droplets, air, and vapor, the degree of vaporization, the droplet size distribution, and the gas flow properties. Data on fuel-air mixing is being sought in this study through the use of a special nonintrusive optical instrument. This data will be used to calibrate and verify an analytical computer model of fuel-air preparation sections being developed in the following project.

Analytical Modeling of the Operating Characteristics of Premixing-Prevaporizing Fuel-Air Mixing Passages. This project is developing a computer model to analytically predict the distribution of liquid and vapor fuel in the airstream of a premixing-prevaporizing passage, after injection of a finely atomized liquid fuel spray into the airstream. The development of this model will be supported with data from the previously mentioned experimental program. This model will be helpful in optimizing mixing passage designs, and for calculating the gas properties entering the burning zone for combustor performance and emissions predictions.

Fuel Sprays in High-Speed Air Flows. A NASA grant is underway at Purdue University to determine the droplet size distribution and droplet number density as a function of position in sprays formed by a fuel injector in a high-speed airflow. Different injectors will be studied in airflows under a range of inlet conditions (fuel-air mixture ratio, air velocity, air pressure, air temperature). This information will form a basis of comparison among fuel injectors and will provide information which can be used to develop theories of the spray dynamics for the purpose of modeling this aspect of combustor phenomena.

Effect of Operating Variables on Emissions. This project is a NASA grant with the University of Michigan and aimed at operating a research combustor under realistic conditions such that the influence of individual variables, particularly fuel spray characteristics, on emissions can be determined. The combustor allows independent control over fuel spray drop size, fuel-air ratio, air inlet temperature, pressure, reference velocity and residence time.

Fuel Distribution Studies. The objective of this test project is to determine the effects of the degree of fuel vaporization and local equivalence ratio distribution on $NO_x$ emissions. This project is an extension of the low pressure (3 atmospheres) work done under the lean combustion element to pressure and temperature ranges representative of actual advanced gas turbine combustors. This data base will be used to design fuel-air mixing sections for LPP combustors.

Autoignition and Flashback Element

Autoignition of Fuels. The objectives of this research program are to develop a critical experiment capable of determining the freestream autoignition characteristics of aircraft-type fuels in air at elevated temperatures and pressures, and to use this equipment to map the ignition delay times of several hydrocarbon fuel-air mixtures. Part one of the program, the development of an experimental apparatus, has been completed.[20] A schematic of the test rig is shown in Fig. 9. An improved fuel injector to provide a uniform fuel-air ratio across the test duct has been built and tests are to be conducted over a range of conditions including pressures up to 30 atmospheres. Presently available data, shown in Fig. 10, show considerable scatter and more accurate information on ignition delay time is needed to establish maximum permissable premixing passage lengths which avoid the occurrence of autoignition. Detailed autoignition data will be obtained for a variety of fuels, including Jet A, JP-4, and No. 2 diesel oil.

Boundary Layer Autoignition and Flashback Studies. The objective of this project is to determine the characteristics of boundary layer autoignition and flashback phenomena in premixed fuel-air streams. The boundary layer profile present at a flameholder and the surface temperature will control the point where flashback occurs. The low velocity airstream near the wall of a premixing passage could allow autoignition to take place. An operating map of the autoignition and flashback limits as a function of pressure, gas temperature, equivalence ratio, and velocity is being experimentally determined in a test rig shown schematically in Fig. 11. The boundary layer profile is altered by changing the front end of the test plate. Shown in Fig. 12 is a photograph looking through the viewing port of the windowed test section. At the particular test condition shown in the photograph, the inlet conditions were such that autoignition of the fuel-air mixture had occurred in the boundary layer of the test plate.

Engine Interfaces Element

Turbulence Characteristics of Compressor Discharge Flows. Two contract efforts were performed to measure the turbulence intensity and scale in the compressor exit area of two gas turbine engines. Pratt and Whitney Aircraft conducted tests on a JT9D engine;[21] General Electric obtained data on a CF6-50 engine.[22] Information on the compressor exit turbulence level is useful in LPP combustor design. Rapid dispersion of liquid fuel droplets in premixing passages may be accomplished by turbulent diffusion of the fuel droplets across the premixing passage airflow. Also, high intensity turbulence improves fuel droplet evaporation rates. Prior to this program, compressor exit turbulence test data have not been available, probably because of the severe environment for turbulence measurement instrumentation. The test results from the Pratt and Whitney study are summarized in Fig. 13. Data were taken from engine idle to engine approach. At the I.D. (25% span) and mid-span location, the turbulence intensity increased slightly from 6±1% at engine idle to 7±1% at engine approach. At the O.D. (75% span) location the turbulence intensity increased more rapidly from 7.5±0.5% at idle to 15±0.5% at approach.

Results from the General Electric tests are summarized in Table 6. Usable data were obtained only at the engine idle condition at three probe positions. The measured turbulence intensity ranged from 4.8 to 5.6%.

These turbulence data can be used to help simulate compressor exit flow conditions in combustor test rigs for advanced combustion systems. However, the data also indicate that measurements at higher engine power levels are desirable to determine whether shifts in turbulence characteristics occur.

Aircraft Engine Transients Study. A unique flame tube combustor test rig has been designed which will be used to study the effects of flow transients on LPP combustion systems. A schematic of the test rig is shown in Fig. 14. Flow transients to be investigated are those that occur in aircraft gas turbine engines during engine acceleration, deceleration, ignition, altitude relight, and compressor stall. Transient effects on the safe and reliable performance of LPP combustor systems may be severe. Even though some of the flow transients are of relatively short duration (10 msec), the possibility exists for the flame flashing back and stabilizing within the premixing duct. A fast-acting valve will generate a programmed flow transient upstream of the flame tube combustor. Data will be obtained to establish an understanding of flame stability associated with transients in these advanced combustor designs.

Summary of Fundamental Studies Phase

A considerable number of projects have very briefly been described in this paper. The information obtained from these completed projects have expanded the available data base of fundamental information on lean, premixed, prevaporized combustion. This data base will be used in the design of combustor concepts for the Phase II, Combustor Concept Screening portion of the program which is scheduled to begin later this year (1979). As more information becomes available from projects still continuing, this new data will be available for use in the Combustor Refinement Phase of the program.

Before closing the discussion on these Fundamental Studies, it should be mentioned that this work has much direct application to advancing the technology of another promising technique which produces very low pollutant emission levels: catalytic combustion. The concept of catalytic combustion offers the potential of even further reducductions in pollutant emissions. By placing a catalyst bed, consisting of a ceramic honeycomb-type substrate impregnated with catalytic material, into the main burner of the combustor, efficient combustion may take place at even leaner overall equivalence ratios. Flame temperatures are low enough that virtually no $NO_x$ is produced whatsoever. In general, all of the problem areas identified above in LPP combustion apply equally well to the catalytic combustion technique. Therefore, the data base acquired in the Fundamental Studies Phase of the SCERP program can prove quite valuable to this very interesting catalytic combustion technology area. Of course, there are unique problem areas in this field associated with catalysts and substrate materials which also need to be addressed. While considerable progress has been made in the last few years,[23] considerable more effort in these areas will be required. A joint NASA and Air Force program is studying the application of catalytic combustion for aircraft gas turbine engines. An overview of the program is given in Ref. 24.

## Concluding Remarks

Projected engine emission levels for lean premixed prevaporized combustors are within the SCERP Program emission goals of Table 1, based on flame tube data from small research rigs. The actual emission levels eventually realized in the engine verification tests of Phase IV of the SCERP Program may be somewhat different when these emission control techniques are developed into operational engine hardware. Trade-offs between emissions, performance, altitude relight capability, durability, maintainability, and complexity will be evaluated. The influence of the actual engine environment as opposed to carefully controlled rig experiments will also have to be considered.

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TABLE 1. - POLLUTANT EMISSION GOALS

| A. EPA landing-takeoff cycle, EPAP[a] | | | |
|---|---|---|---|
| Pollutant | ECCP results | | Program goal |
| | CF6-50[b] | JT9D-7[c] | |
| Total hydrocarbons | 0.3 | 0.2 | 0.3 |
| Carbon monoxide | 6.2 | 3.2 | 2.2 |
| Oxides of nitrogen | 5.7 | 2.7 | 2.2 |
| **B. Engine cruise condition, emission index[d]** | | | |
| Pollutant | Current engines | | Program goal |
| Oxides of nitrogen | 16-22 | | 3.0 |

[a]lb-mass/1000 lb-force · hr/cycle.
[b]Ref. 8.
[c]Ref. 7.
[d]gm/kg fuel.

TABLE 2. - PERFORMANCE GOALS

| Parameter | Value | Engine condition |
|---|---|---|
| Combustion efficiency $\eta$ | $\geq$99.9% | Takeoff |
| | $\geq$99.5% | Idle |
| | >99% | All other |
| Pressure loss $\Delta P/P$ | $\leq$5.5% | All |
| Burner outlet temperature: | | |
| Pattern factor | $\leq$0.25 | Takeoff, cruise |
| Profile factor | $\leq$.15 | Takeoff, cruise |
| Maximum combustor liner temperature | 1150 K | All |



TABLE 3. - OPERATION GOALS

| |
|---|
| Superior altitude relight characteristics |
| Minimum impact on engine cycle, performance, and weight |
| Good mechanical integrity and reliability |
| Long combustor liner life |
| No fuel coking |
| Minimum additional design complexity |
| Stable operation during engine transients |

TABLE 4. - SCERP PROGRAM SCHEDULE

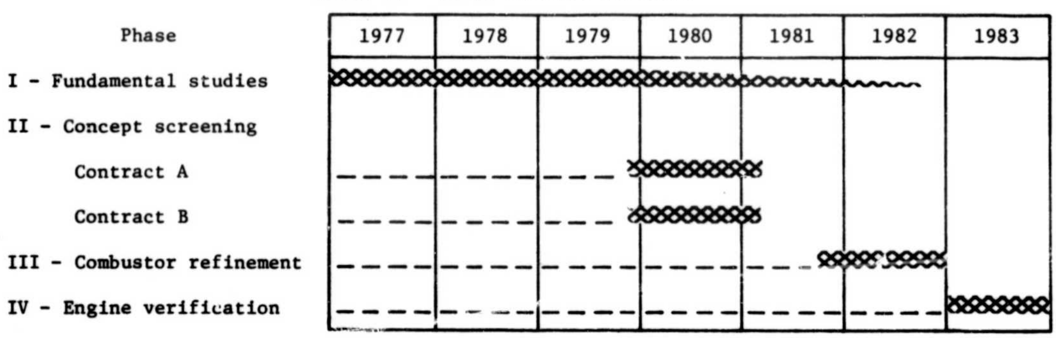
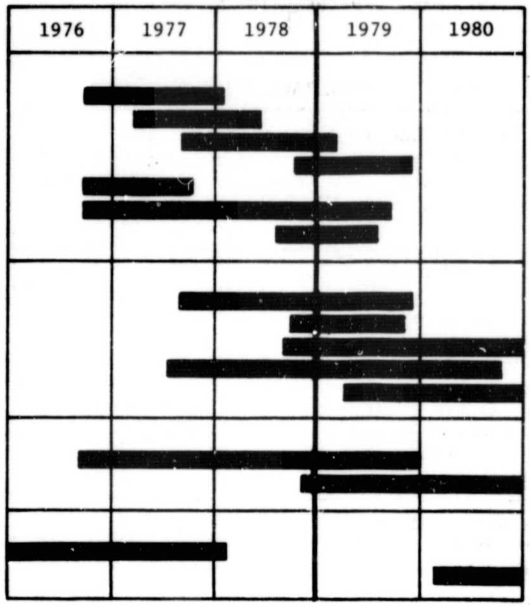


TABLE 5. - SCERP PROGRAM PHASE I: FUNDAMENTAL STUDIES

Calendar year




**Program elements:**

A. Lean combustion
- Effect of cycle pressure (GASL)[a]
- Flameholder geometry study (GASL)[a]
- Lean stability augmentation (UTRC)[a]
- Secondary air dilution (GASL)
- Flameholder blockage study (IH)[a]
- Fuel preparation effects (IH)[a]
- LPP concept study (GE, P & WA)[a]

B. Fuel-air preparation
- Fuel preparation data (SOLAR)[a]
- Fuel preparation model (UTRC)[a]
- Drop-size characteristics (PURDUE)
- Effect of operating variables (MICHIGAN)[a]
- Fuel distribution studies (IH)

C. Autoignition & flashback
- Autoignition of fuels (UTRC)[a]
- B-L autoignition & flashback studies (IH)

D. Engine interfaces
- Compressor discharge turbulence (P & WA, GE)[a]
- Engine transients study (IH)

[a]Participant in Ref. 12.

TABLE 6. - TURBULENCE TEST DATA FOR CF6-50 TESTS

| Data point number | 95 | 106 | 106 | 106A | 106A | 106A |
|---|---|---|---|---|---|---|
| Probe position | Inner | Inner | Outer | Inner | Center | Outer |
| Calculated velocity - m/sec | 68.3 | 69.2 | 69.2 | 68.6 | 76.2 | 68.6 |
| Turbulence - m/sec | 3.26 | 3.66 | 3.44 | 3.60 | 4.27 | 3.84 |
| Turbulent intensity - % | 4.8 | 5.3 | 5.0 | 5.2 | 5.6 | 5.6 |
| Turbulent miscoscale - cm | .73 | .94 | .85 | .79 | .98 | .91 |
| Turbulent length scale - cm | 6.58 | 6.04 | 5.73 | 5.64 | 6.95 | 5.97 |

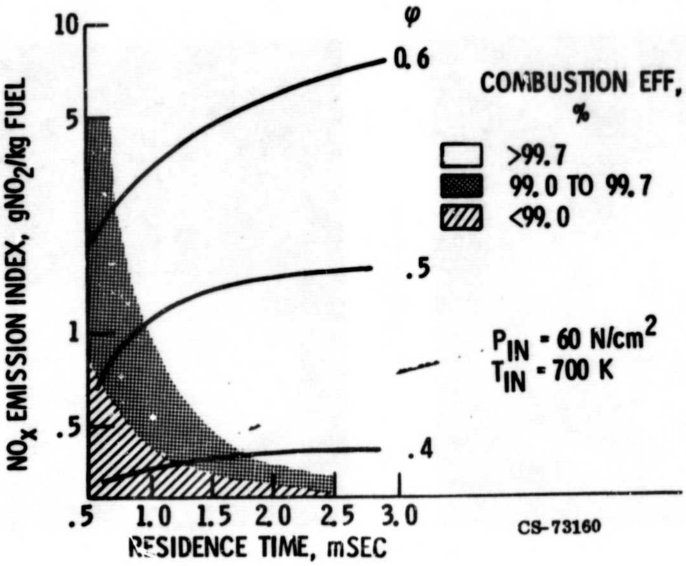



Figure 1. - Effect of residence time on $NO_x$ and efficiency in a premixed fuel and air flame tube.



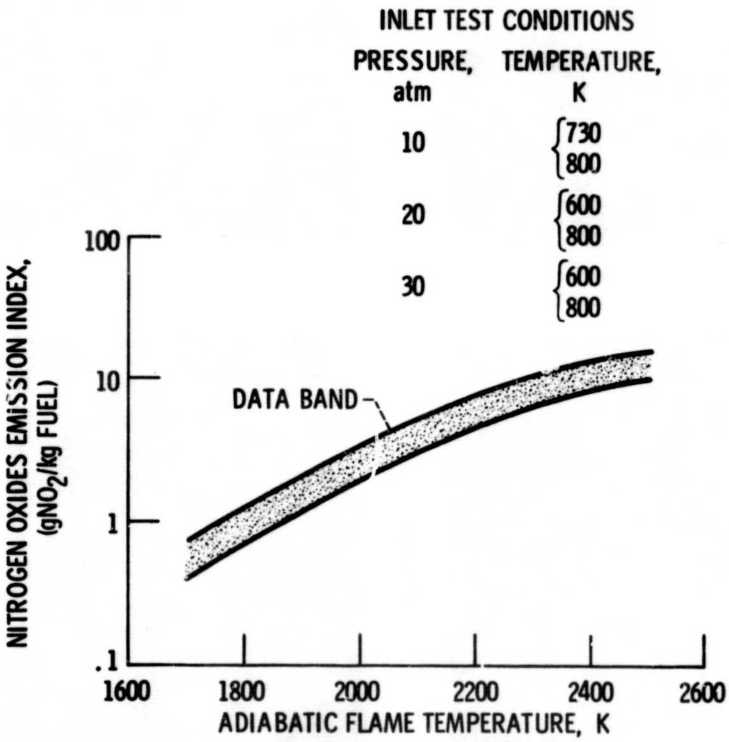



Figure 2. - Effect of pressure on emissions: over the range of pressures from 10 to 30 atmospheres, no effect of pressure on $NO_x$ emissions was found when when correlated against adiabatic flame temperature.

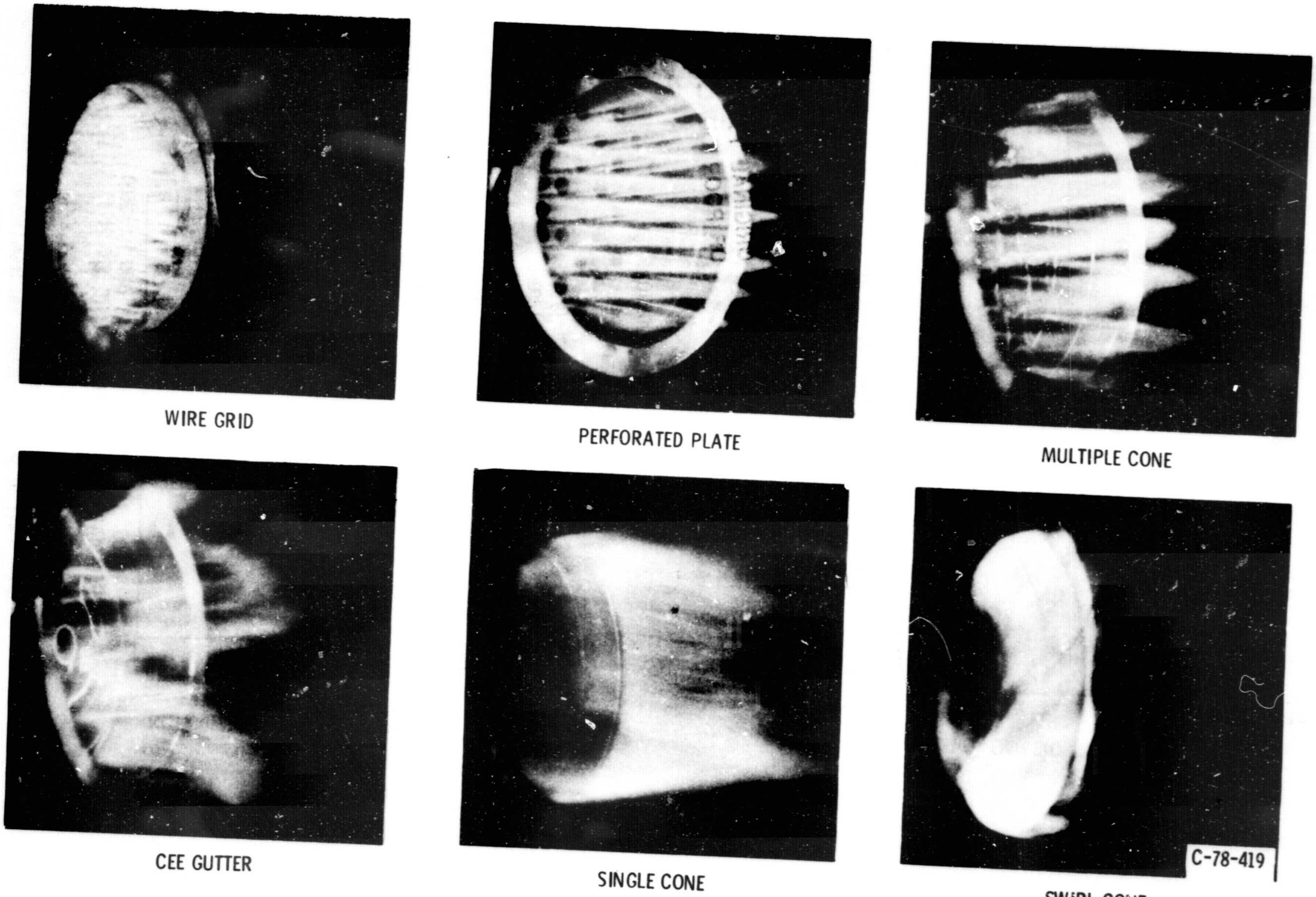



Figure 3. - Open duct operation of six flameholders at 70 percent blockage.

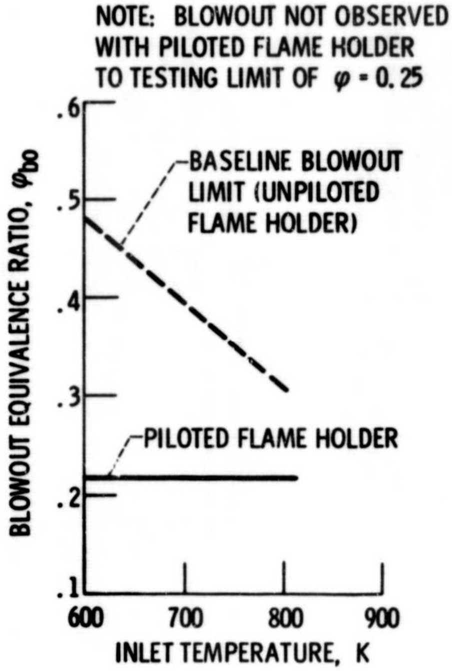



Figure 4. - Combustor blowout limits: comparison of piloted flame holder with baseline (unpiloted flame holder).

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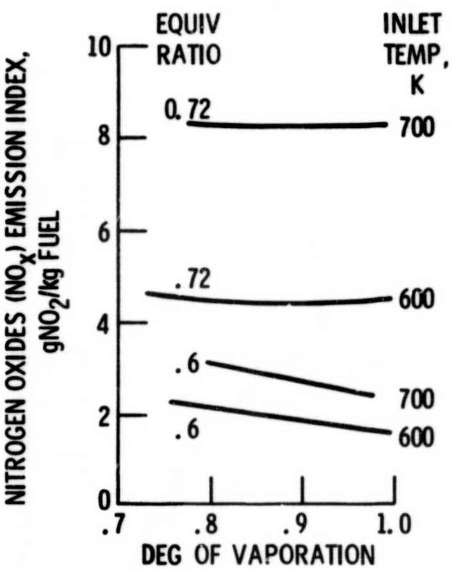


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Figure 5. - Effect of degree of vaporization on $NO_x$ over a range of inlet temperature and equivalence ratios.

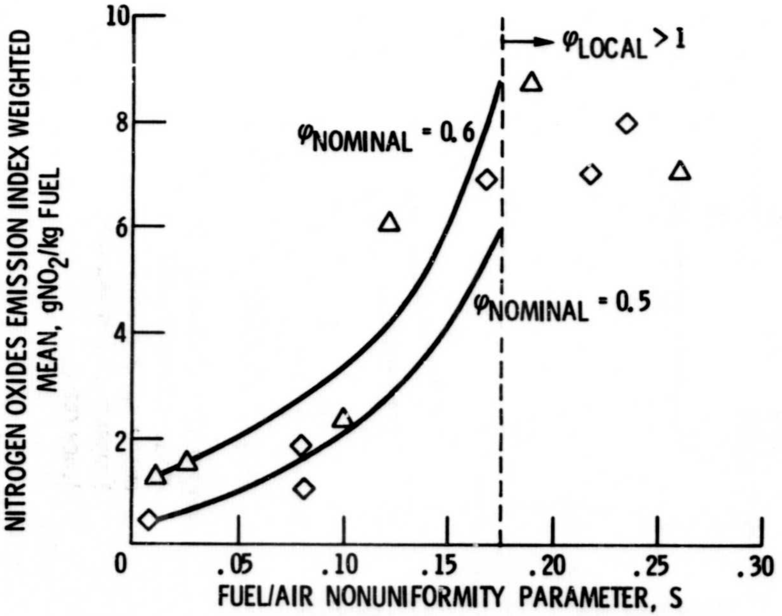



Figure 6. - Effect of fuel/air nonuniformity on $NO_x$ emissions for two nominal equivalence ratios ($\varphi$). Inlet air temperature of 600 K.

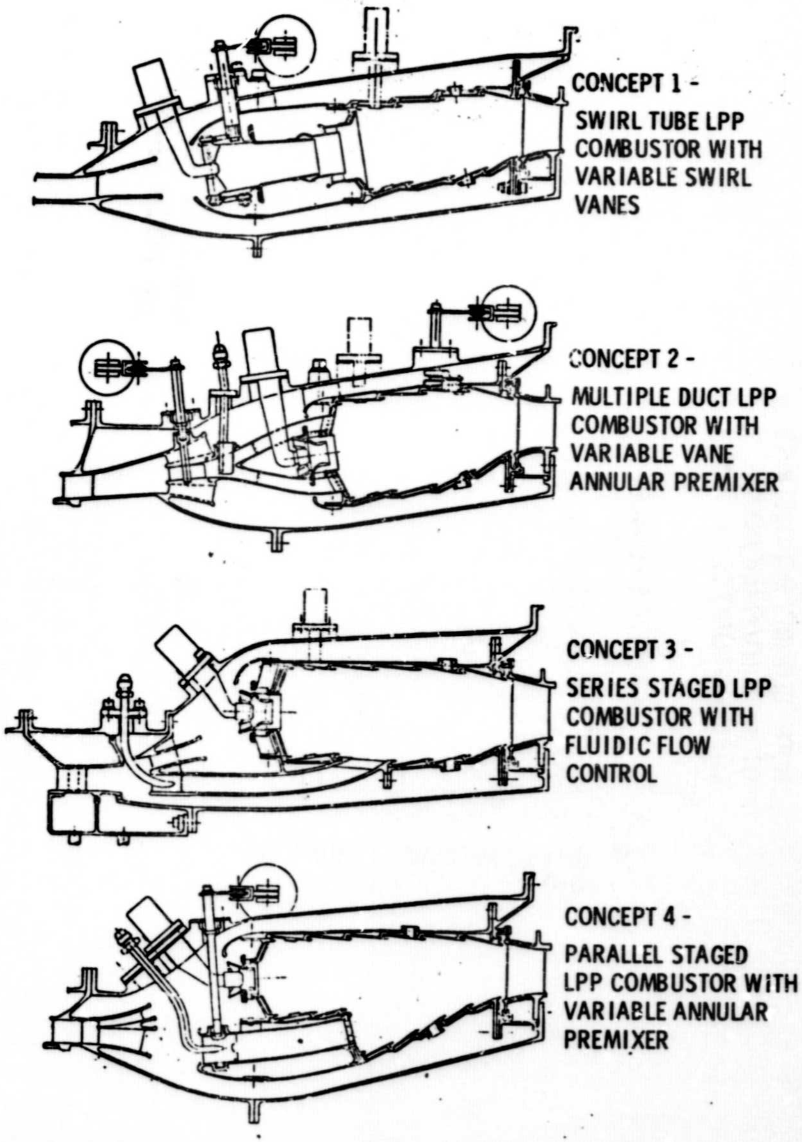
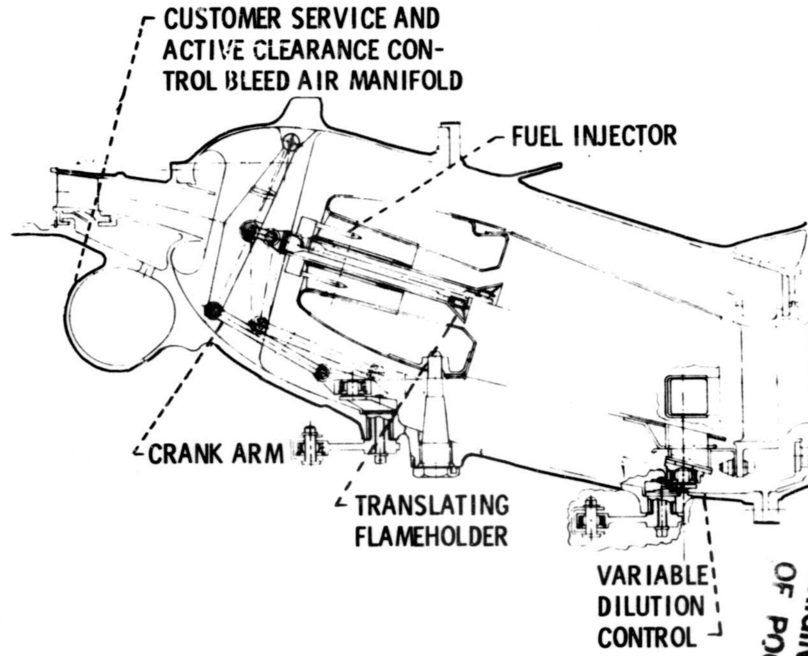
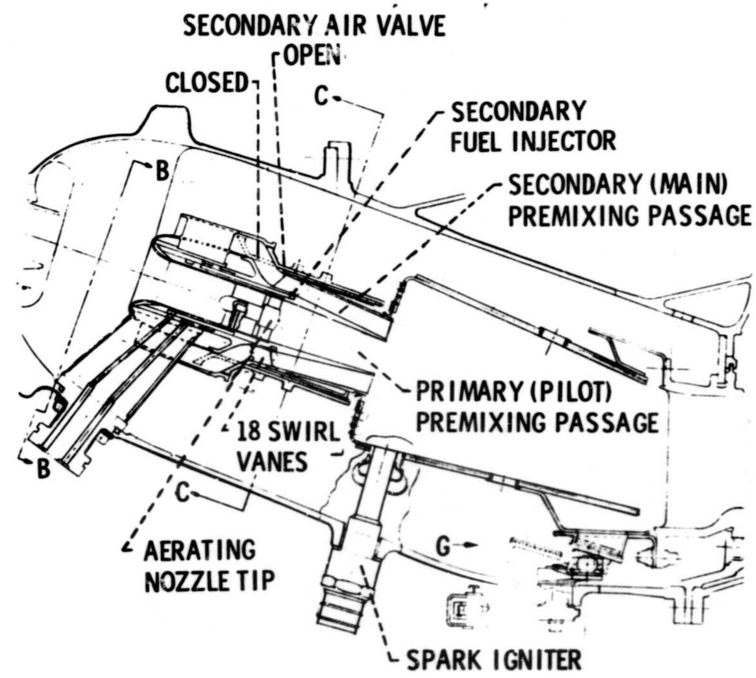



Figure 7. - Combustor concepts for General Electric's "LPP Combustor Conceptual Design Study."

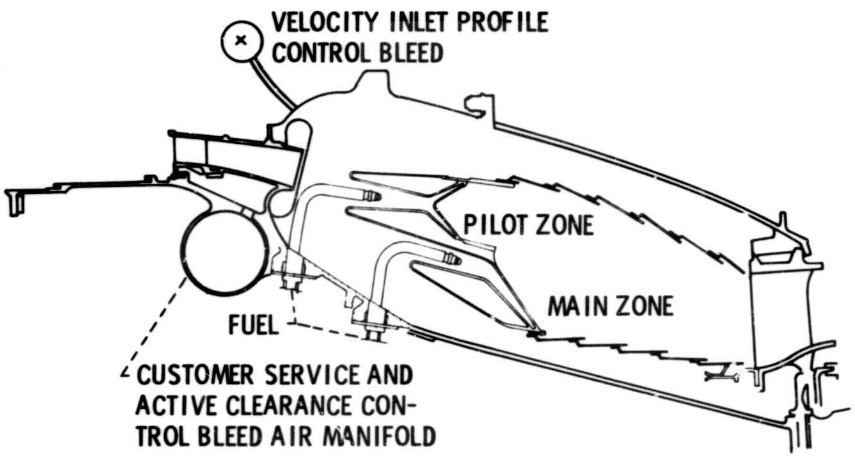



Concept 1 - Translating Premixing Passage

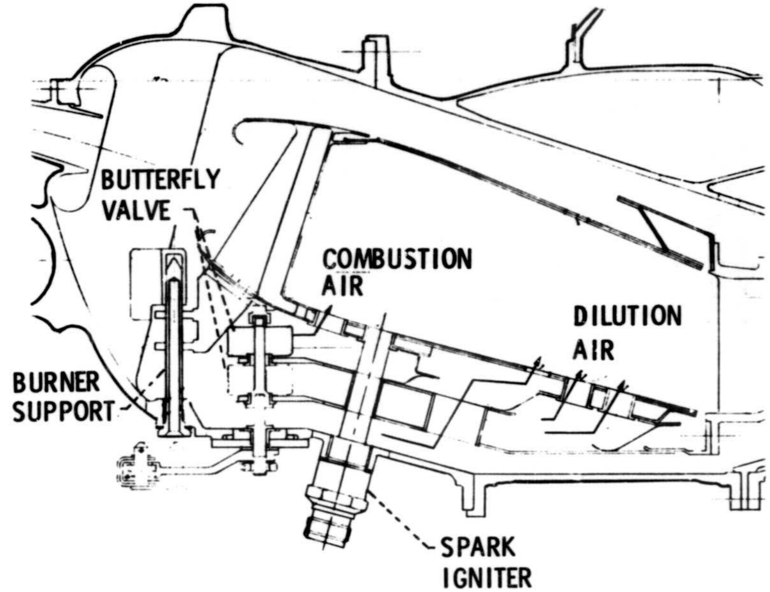



Concept 2 - Swirl Premix Tubes






Concept 3 - Dual Stage Premixed/Prevaporized




Concept 4 - Dilution Air Valve Control

Figure 8. - Combustor concepts for Pratt & Whitney's "LPP Combustor Conceptual Design Study."

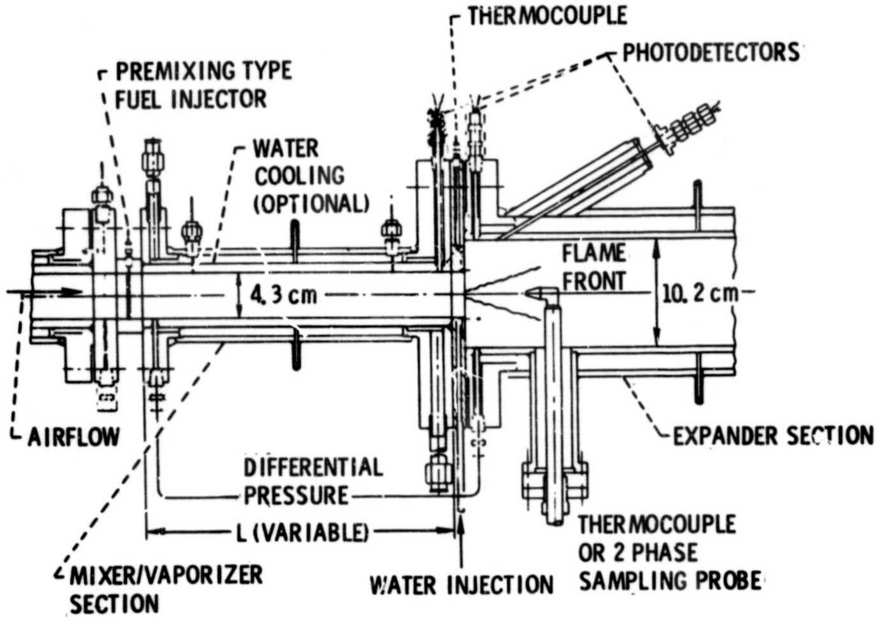



Figure 9. - Autoignition test section.

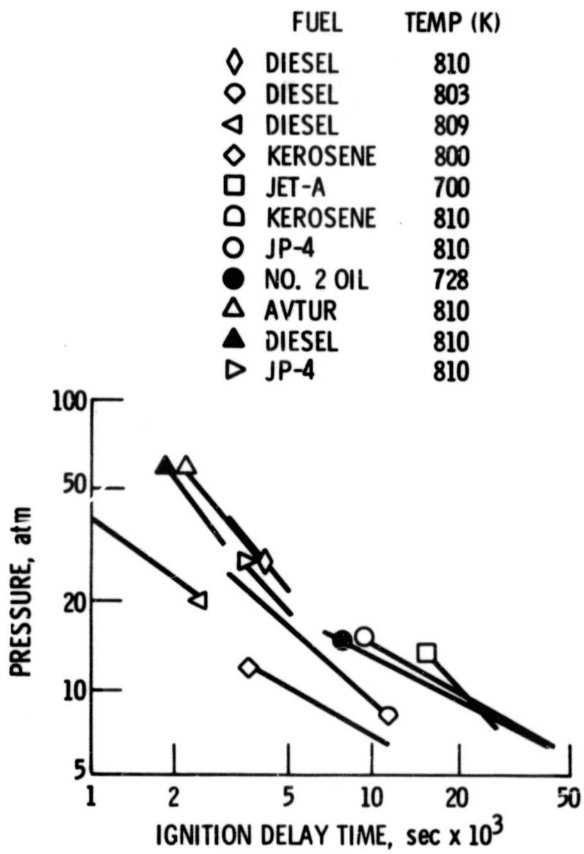



Figure 10. - Correlation of presently available ignition delay data.

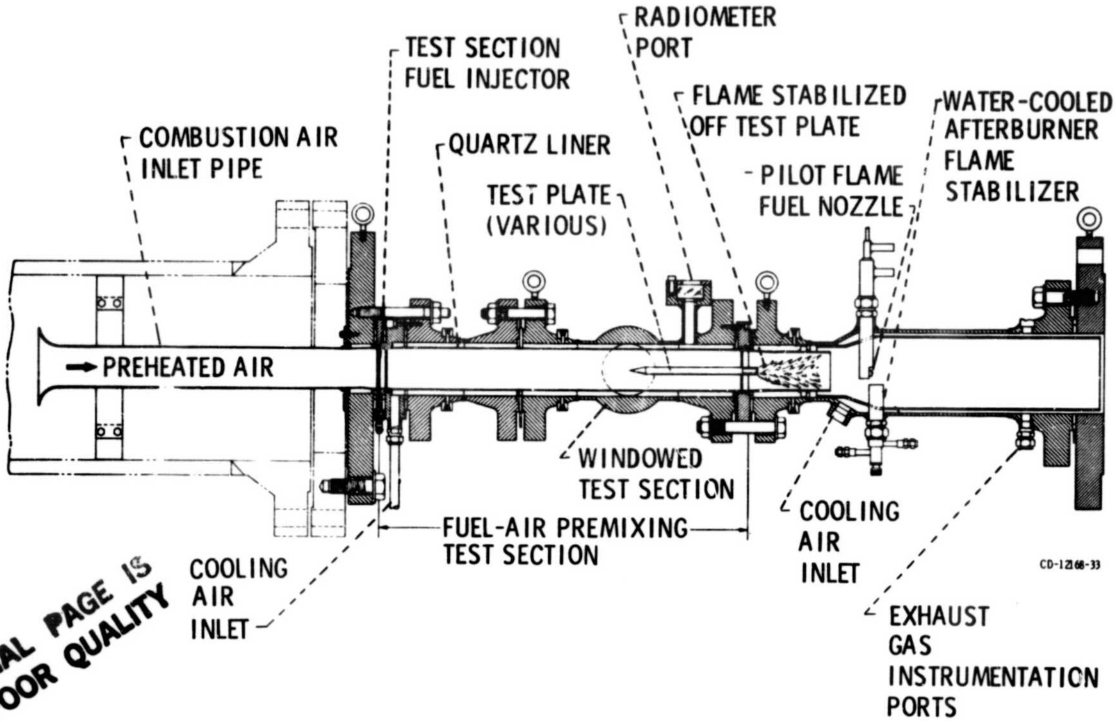





Figure 11. - Test rig for surface induced autoignition/flashback study.

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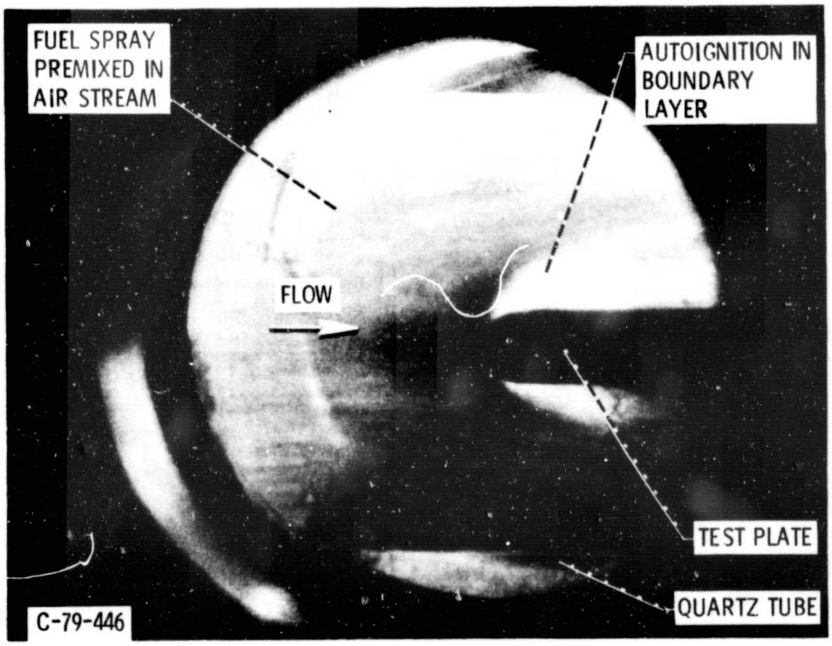


Figure 12. - Study of boundary layer autoignition and flashback phenomena: autoignition along boundary layer of a test plate in premixed fuel and air stream.

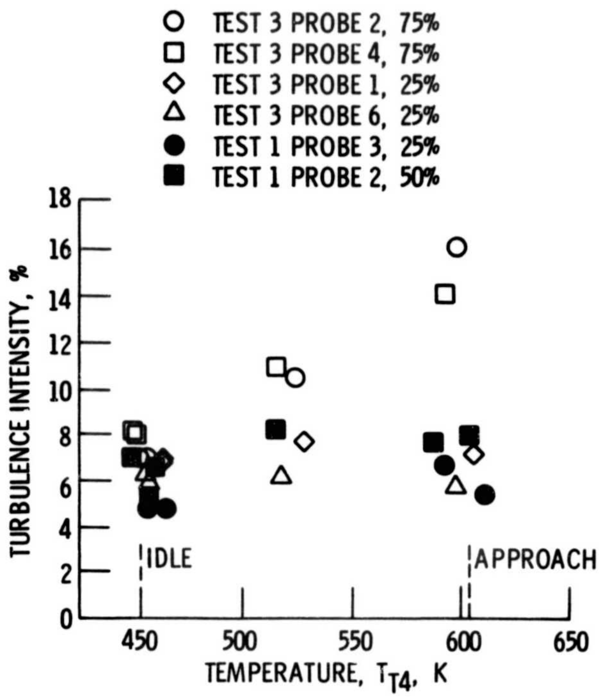


Figure 13. - Dependence of turbulence on engine operation for JT9D tests.

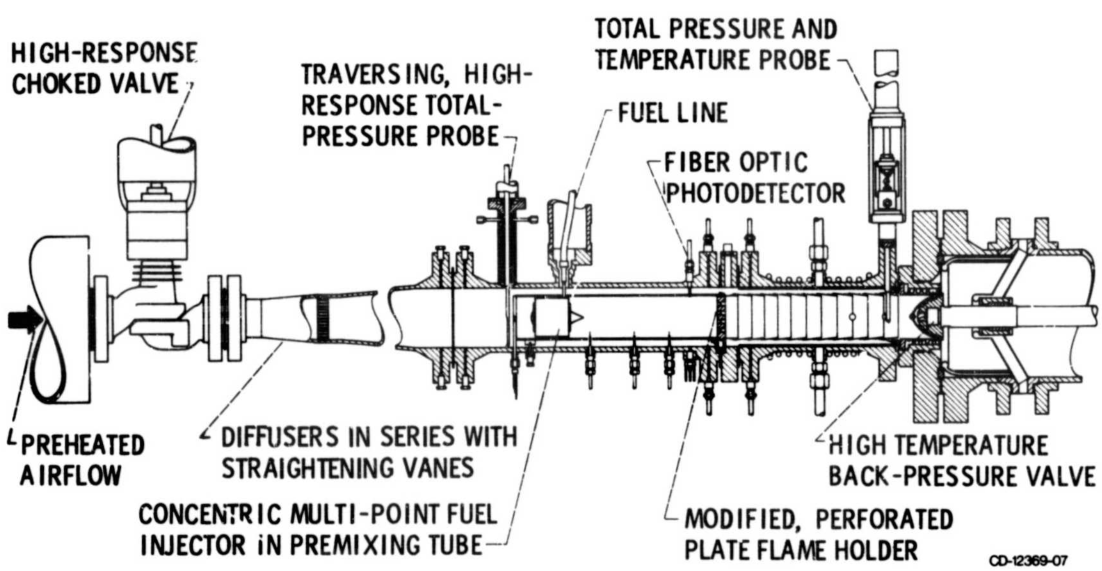


Figure 14. - Transient-flow study combustor rig.